



## UNITED STATES AIR FORCE RESEARCH LABORATORY

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# EVALUATION OF THE SNAPSHOT 3D HEAD-RELATED TRANSFER FUNCTIONS MEASUREMENT SYSTEM

Douglas S. Brungart  
W. Todd Nelson  
Robert Bolia

HUMAN EFFECTIVENESS DIRECTORATE  
CREW SYSTEM INTERFACE DIVISION  
WRIGHT-PATTERSON AIR FORCE BASE OH 45433-7022

Robert Tannen

UNIVERSITY OF CINCINNATI  
2624 CLIFTON AVE  
CINCINNATI OH 45221

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Human Effectiveness Directorate  
Crew System Interface Division  
2255 H Street  
Wright-Patterson AFB OH 45433-7022

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MARIS M. VIKMANIS  
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Air Force Research Laboratory

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13. ABSTRACT (Maximum 200 words) The SNAPSHOT MX is a system designed to collect individualized Head-Related Transfer Functions (HRTFs) quickly and efficiently in non-anechoic rooms. The system, which consists of a signal processing workstation, a speaker stand, and a pair of microphones that are inserted into the ears of the subject, uses Golay codes to measure the time-domain impulse response of the transfer function from the speaker to the in-ear microphones. The impulse responses are then windowed to eliminate the effects of room reverberation and stored in an acoustic head map (AHM) file for rendering with the Convolvotron virtual audio display. This report outlines the SNAPSHOT system and presents the results of a study comparing auditory localization performance with individualized HRTFs measured with the SNAPSHOT to generic HRTFs measured with the SNAPSHOT on the Knowles Electronics Manikin for Acoustic Research (KEMAR) and to the generic SDO transfer functions packaged with the Convolvotron. The results indicate that localization performance is significantly worse with the individualized SNAPSHOT HRTFs than with the generic SDO HRTFs.				
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## PREFACE

The work described herein was performed at the Crew System Interface Division, Air Force Research Laboratory. Rob Tannen and Todd Nelson, who were interested in using the SNAPSHOT system to collect HRTF measurements for use in the Synthesized Immersion Research Environment (SIRE) Facility, provided the motivation for this experiment. The authors would like to thank Mark Ericson for his helpful comments on the experiment. Funding for the study was supplied by the US-French Super-Cockpit Joint Research Program.

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# TABLE OF CONTENTS

<b>Preface</b>	<b>iii</b>
<b>List of Figures</b>	<b>vi</b>
<b>1.0 Introduction</b>	<b>1</b>
<b>2.0 The SNAPSHOT system</b>	<b>2</b>
2.1 Origins of the SNAPSHOT system . . . . .	2
2.2 Description of the SNAPSHOT system . . . . .	2
2.3 Transfer function measurement with the SNAPSHOT system . . . . .	4
2.4 SNAPSHOT measurement procedure . . . . .	5
<b>3.0 Psychophysical evaluation of SNAPSHOT measurement system.</b>	<b>7</b>
3.1 Methods . . . . .	7
3.1.1 Subjects . . . . .	7
3.1.2 HRTF measurements . . . . .	7
3.1.3 Stimulus . . . . .	8
3.1.4 Response . . . . .	8
3.1.5 Procedure . . . . .	8
3.2 Results . . . . .	8
3.2.1 Front-back reversals . . . . .	8
3.2.2 Angular errors . . . . .	10
3.2.3 Azimuth and elevation errors . . . . .	10
3.3 Discussion . . . . .	11
3.3.1 Poor overall performance . . . . .	11
3.3.2 Evaluation of the HRTF measurements with the SNAPSHOT . . . . .	13
3.3.3 Explanations for poor performance with the SNAPSHOT . . . . .	13
<b>4.0 Conclusions and Recommendations</b>	<b>15</b>
<b>5.0 References</b>	<b>16</b>

## LIST OF FIGURES

FIGURE		PAGE
1	Alphatron EL signal processing workstation. . . . .	3
2	Adjustable speaker and stand. . . . .	3
3	In-ear microphones. . . . .	4
4	Transfer function collection with the SNAPSHOT system. . . . .	5
5	Percentage of front-back reversals. . . . .	9
6	Overall angular error. . . . .	10
7	Standard deviation of error in azimuth and elevation. . . . .	12



## 1.0 INTRODUCTION

Over the past decade, there has been considerable interest in the use of virtual audio displays to reduce operator workload in challenging working environments, such as aircraft cockpits. These virtual audio displays use digital signal processing technology to add spatial information to sound sources presented over headphones. The spatial information is encoded in the Head-Related Transfer Function (HRTF), which represents the transformations that occur in a sound wave as it propagates from a distant sound source to the left and right ears of a listener. Specifically, the HRTF encodes three types of spatial information: 1) The interaural time delay between the arrival of the sound at the closer ear and the arrival of the sound at the more distant ear; 2) The interaural intensity difference, caused by the acoustic shadowing of the sound by the head at the more distant ear; 3) Direction-dependent spectral cues caused by the filtering of the outer ear or pinna. An extensive review of auditory display technology is provided by Wenzel (1991).

Many researchers have noted that the direction-dependent properties of the pinna, which are known to be extremely important in determining the elevation of a sound source, depend on the complicated geometry of the outer ear and vary substantially across listeners (Butler, 1987). Thus, it is believed that listeners can localize more accurately with HRTFs collected from their own ears than with a generic HRTF collected from another person's ears (Wenzel, Arruda, Kistler, & Wightman, 1993). However, the collection of HRTFs can be a tedious process that requires an elaborate experimental apparatus and access to an anechoic chamber.

This report evaluates the SNAPSHOT MX, a commercial system that was designed to allow rapid collection of individualized HRTFs in relatively small, non-anechoic rooms. The system is designed to produce HRTF files that can be implemented with the Convolvotron virtual audio display system. The first section provides a detailed description of the SNAPSHOT. The second section describes the results of a psychoacoustic validation study that compares auditory localization performance with (1) individualized HRTFs collected with the SNAPSHOT system; (2) a generic set of transfer functions provided with the Convolvotron; and (3) a generic set of transfer functions measured with the SNAPSHOT.

## 2.0 THE SNAPSHOT SYSTEM

### 2.1 Origins of the SNAPSHOT system

The SNAPSHOT is a product of Crystal River Engineering, a subsidiary of Aureal Semiconductor located in Fremont, California. The system tested in this evaluation, the SNAPSHOT MX version 1.3, was produced in 1996. The SNAPSHOT MX v 1.3 was apparently a pre-production version of the SNAPSHOT system, as the manuals provided are incomplete and marked DRAFT, and many of the software components described in the manual are non-functional. The SNAPSHOT product line, along with the related Convolvotron product line, has been discontinued by Aureal Semiconductor and technical support for the system is no longer available.

### 2.2 Description of the SNAPSHOT system

The SNAPSHOT system consists of three major components:

**Alphatron EL Workstation:** The Alphatron EL workstation is a signal processing system based on a Pentium PC running Windows95 (Figure 1). The Alphatron EL is equipped with a proprietary sound card with two D/A output channels and two A/D input channels, and a standard commercial sound card with two A/D inputs and two D/A outputs. The software for the SNAPSHOT system, which was preloaded at the factory, is written in MATLAB and in pre-compiled MATLAB MEX modules. The Alphatron workstation is the heart of the SNAPSHOT system, responsible for signal generation and processing.

**Speaker and Speaker Stand:** The SNAPSHOT uses a Bose Acoustimass speaker, attached to an adjustable height stand, to make the HRTF measurements (Figure 2). The stand is approximately 1.8 m tall and can be used to place the loudspeaker at elevation angles ranging from  $-36^\circ$  to  $+54^\circ$ . A Sony commercial receiver/amplifier is provided for driving the loudspeaker.

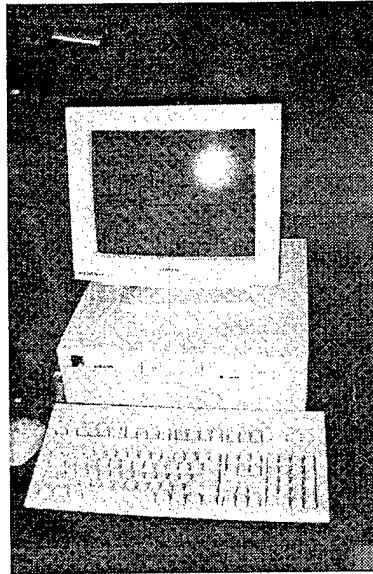


Figure 1: Alphatron EL signal processing workstation.

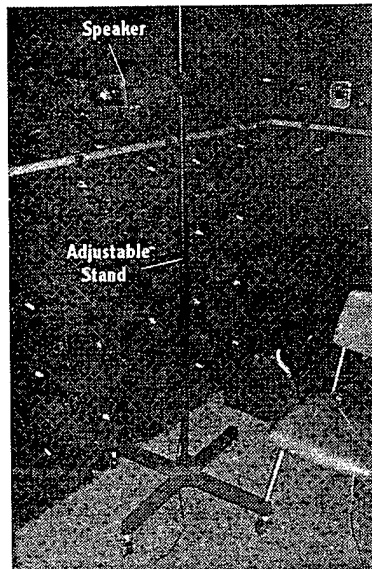


Figure 2: Adjustable speaker and stand.

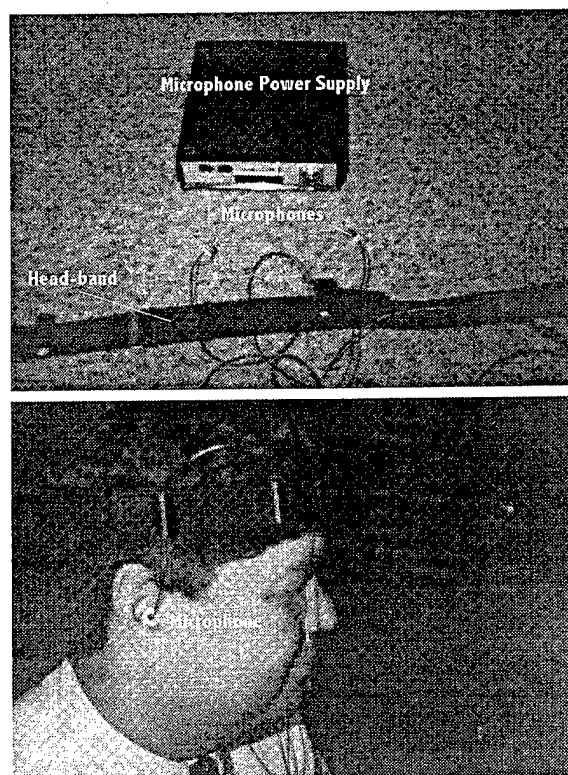


Figure 3: In-ear microphones shown with the microphone power supply (top) and inserted in the subject's ears (bottom).

**Blocked Meatus Microphones:** The SNAPSHOT includes a pair of small microphones that are placed in the ears of the subject during the SNAPSHOT measurements (See Figure 3). The microphones are designed to be manually placed in the ear canal opening and to completely block the ear canal. This type of HRTF measurement is known as a blocked-meatus measurement (Moller, Sorensen, Hammershoi, & Jensen, 1995).

### 2.3 Transfer function measurement with the SNAPSHOT system

The SNAPSHOT system uses a transfer function measurement technique based on Golay codes. Golay codes are special pairs of binary sequences  $A$  and  $B$  such that the sum of the autocorrelation of sequence  $A$  and the autocorrelation of sequence  $B$  has only a single non-zero value (i.e. is an impulse). The use of Golay codes allows a very rapid HRTF measurement with an acceptable signal-to-noise ratio. This is achieved by playing the complementary Golay sequences  $A$  and  $B$  out of the loudspeaker (allowing sufficient time between the two sequences for the sound field to decay), recording the responses to the sequences

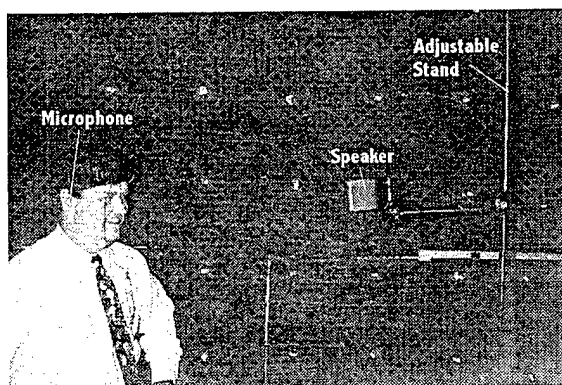


Figure 4: Transfer function collection with the SNAPSHOT system.

from each microphone, convolving each output sequence the time-reversed version of the input sequence, and summing the two convolved sequences to determine the impulse response of the complete system (sound card, amplifier, loudspeaker, HRTF, and microphone). [The Golay-code based HRTF collection process is described in more detail in Foster (1986).]

The SNAPSHOT system was specifically designed to measure the HRTF in reverberant rooms. This is achieved by time-windowing the measured impulse responses to capture the part of the impulse response related to the direct sound path from the speaker to the head and to ignore the later parts of the impulse response caused by sound reflections off the walls of the room.

## 2.4 SNAPSHOT measurement procedure

The SNAPSHOT procedure allows a single experimenter to collect a set of 72 HRTFs from a subject in less than 30 minutes. The procedure can be summarized as follows:

1. The subject is examined with an otoscope and the microphones are wrapped in a seal constructed of acoustic foam and inserted into the subject's ear canals. A velcro band wrapped around the subject's head holds the microphone leads in place and prevents them from pulling out the microphones (Figure 3).
2. The subject is seated on a swivel chair located 1.0 m from the loudspeaker. The SNAPSHOT requires the area in the room within 0.7 m of the loudspeaker and the subject to be free of reflecting objects in order to eliminate reverberant sound from the transfer function measurement.

3. The HRTFs are collected by rotating the swivel chair through 12 positions in azimuth (every  $30^\circ$ ) and measuring the left and right HRTFs at each position. The 12 positions are repeated at each of six different speaker heights, ranging from  $54^\circ$  in elevation to  $-36^\circ$  in  $18^\circ$  increments. Thus, a total of 72 HRTF measurements are made for each ear.
4. The SNAPSHOT processes the measured HRTFs and archives them into a ".AHM" file, a proprietary format for use in the Crystal River Engineering Convolvotron audio display system. This processing is not described in any detail in the SNAPSHOT manual, but it apparently is designed to remove the characteristics of the microphone and speaker as well as the reverberation characteristics of the room.

## **3.0 PSYCHOPHYSICAL EVALUATION OF SNAPSHOT MEASUREMENT SYSTEM**

In order to evaluate the effectiveness of the SNAPSHOT system for collecting accurate HRTF measurements, a simple psychoacoustic experiment was performed. In this experiment, the localization accuracy of three subjects was tested with the "SDO" HRTFs provided with the Convolvotron, with their own HRTFs measured with the SNAPSHOT, and with measurements made on a KEMAR manikin with the SNAPSHOT.

### **3.1 Methods**

#### **3.1.1 Subjects**

Two males and one female, ages 20-35, served as subjects in the experiment. All reported normal hearing in both ears. Two of the subjects had considerable experience with the experimental procedure from participating in an unrelated localization experiment (using the same paradigm and response method) over the previous two months. One of the subjects had no experience in auditory localization studies.

#### **3.1.2 HRTF measurements**

The SNAPSHOT measurement system was used to measure a full set of 72 HRTFs on each of the three subjects using the procedure outlined in the previous section. In addition, a full set of HRTF measurements was made on a KEMAR acoustic manikin with the microphones inserted in the ear canal openings of the rubber pinnae provided with KEMAR. The SNAPSHOT system was used to archive the HRTFs in the ".AHM" file format for use with the Convolvotron system. In addition, the "SDO" HRTF files, which were measured originally by Wightman and Kistler (1989) and are provided with the Convolvotron, were used as a control.

### **3.1.3 Stimulus**

The auditory stimulus used in the experiment consisted of short (300ms) bursts of pink noise presented binaurally over headphones. The noise, produced by a GenRad 1382 noise generator, was used as an input signal for the Convolvotron, which added localization cues to the signal by convolving the noise with the HRTFs stored in the ".AHM" files. The output of the Convolvotron was then presented to the subject through Sennheiser HD520 headphones.

### **3.1.4 Response**

The GELP (God's Eye Localization Pointing) method was used to collect subject responses (Gilkey, Good, Ericson, Brinkman, & Stewart, 1995). In the GELP method, the subject is asked to use a stylus to point to the location on the surface of a solid plastic sphere that best matches the perceived direction of the sound source. Gilkey's validation experiments have shown that this method produces a localization error of approximately 10° when responding to verbal coordinates (azimuth and elevation) and of approximately 20° when responding to a free-field directional sound source.

### **3.1.5 Procedure**

In each experimental session, the subject responded to a total of 185 stimuli located at 37 different positions randomly distributed over the surface of the sphere. Each subject participated in a total of three sessions. In the first session, the subjects listened to the "SDO" HRTFs. In the second session, they listened to their own HRTFs previously measured with the SNAPSHOT system. In the third session, they listened to the KEMAR HRTFs. Each session took approximately 20 minutes to complete, and the subjects were given a short break between sessions.

## **3.2 Results**

### **3.2.1 Front-back reversals**

In this experiment, as in previous localization experiments without head motion, the subjects experienced a number of front-back reversals. A front-back reversal occurs when a



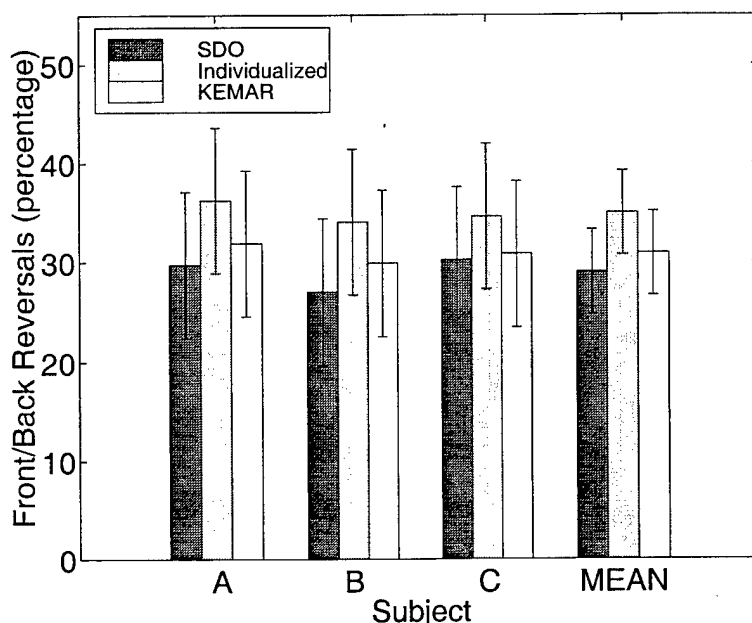


Figure 5: Percentage of front-back reversals for each subject and each type of HRTF. The error bars show the 95% confidence interval.

listener perceives a sound source at the mirror image of its true location across the frontal plane. For example, a sound source at  $45^\circ$  in azimuth might be perceived at  $135^\circ$ . These front-back reversals occur because the dominant interaural cues (interaural time delay and interaural intensity difference) are approximately cylindrically symmetric around the interaural axis of the head (Wallach, 1940), and thus cannot be used to distinguish between symmetric source locations in the front and rear hemispheres.

Front-back confusions occurred in approximately 30% of the trials overall (Figure 5). Each of the three subjects reversed the smallest number of trials with the SDO transfer functions, and the largest number of trials with the individualized transfer functions. However, a two-factor analysis of variance (ANOVA) indicates that neither the main effects of subject nor HRTF type were significant at the  $p < 0.05$  level. The consistency of the pattern of performance across subjects is confirmed by the lack of any interaction between the subject and HRTF factors ( $F_{4,1629} = 0.04509$ ).

Trials where front-back confusions occurred were “corrected” by reflecting the response locations across the frontal plane prior to analyzing the data for directional errors.

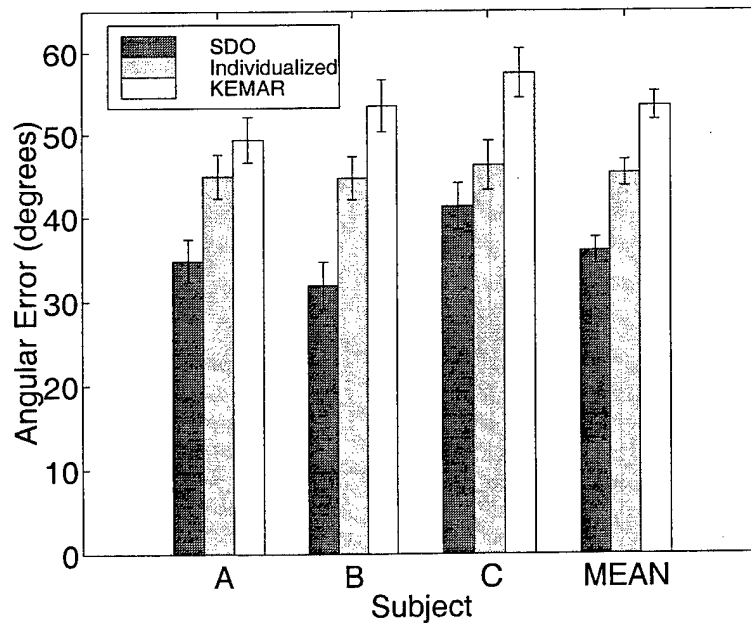


Figure 6: Overall angular error. Front-back reversals have been corrected in these data. The error bars show the 95% confidence intervals.

### 3.2.2 Angular errors

The angular error is defined as the angle of arc between the stimulus vector (the vector from the origin to the stimulus location) and the response vector (the vector from the origin to the response location). The angular error represents the overall error between the stimulus and response locations and includes the effects of both azimuth and elevation errors. In this experiment, the overall angular error was consistently lowest with the SDO transfer functions, and highest with the KEMAR transfer functions (Figure 6). A two-factor repeated measures ANOVA indicates that the main effects of subject and transfer function type are both significant at the  $p < 0.05$  level.

### 3.2.3 Azimuth and elevation errors

The relative contributions of the errors in azimuth and elevation can be determined from the standard deviation of the azimuth error and the elevation error. The standard deviation is a useful measure because it ignores the effects of systematic bias in the results and concentrates only on response variability. The results indicate that most of the variation in error across transfer functions is a result of errors in the azimuth of the sound source rather

than the elevation of the sound source (Figure 7).

### 3.3 Discussion

#### 3.3.1 Poor overall performance

The overall localization performance measured in this experiment was very poor in each of the three conditions tested. Previous experiments in the free field and with virtual audio displays have shown that human localization performance is substantially better than was indicated in this experiment. For example, Wightman and Kistler (1989) found that the mean overall angular error was approximately  $21.3^\circ$  with a free-field stimulus and  $22.3^\circ$  with a virtual stimulus, compared to an average error of  $35.5^\circ$  in the best condition of this experiment. Similarly, Wightman and Kistler reported reversals in only 5.6% of trials with a free-field stimulus and 9.6% of trials with a virtual stimulus, compared to more than 29% of trials in the best condition of this experiment.

The poor performance observed in this experiment cannot be attributed to the GELP response method, which has been shown to produce angular errors of only  $18.2^\circ$  with a free-field stimulus (Gilkey et al., 1995). The errors do not appear to be a result of a systematic failure of the experimental procedure, as there were significant differences in subject performance across the three conditions and the relative ordering of performance in the three conditions was identical across the three subjects. Training does not appear to be an issue either. Two of the subjects (A and B) had considerable experience with the experimental procedure prior to their experiment, and while the third subject (C) performed considerably worse than the two experienced subjects, the relative results in the three conditions were similar. The performance may be attributable to the interpolation algorithm used by the Convolvotron. Although the Convolvotron is often cited in the literature, we were unable to identify a single study validating its performance in a location identification experiment without head-tracking.

Note that, while overall performance was poor, the differences between performance in the three experimental conditions were significant. Furthermore, these differences cannot be attributed to training effects because the best performance was always seen with the SDO transfer functions that were presented first for each of the subjects. Therefore, although overall performance was poor, the results can still be used to compare performance across the three types of HRTFs.

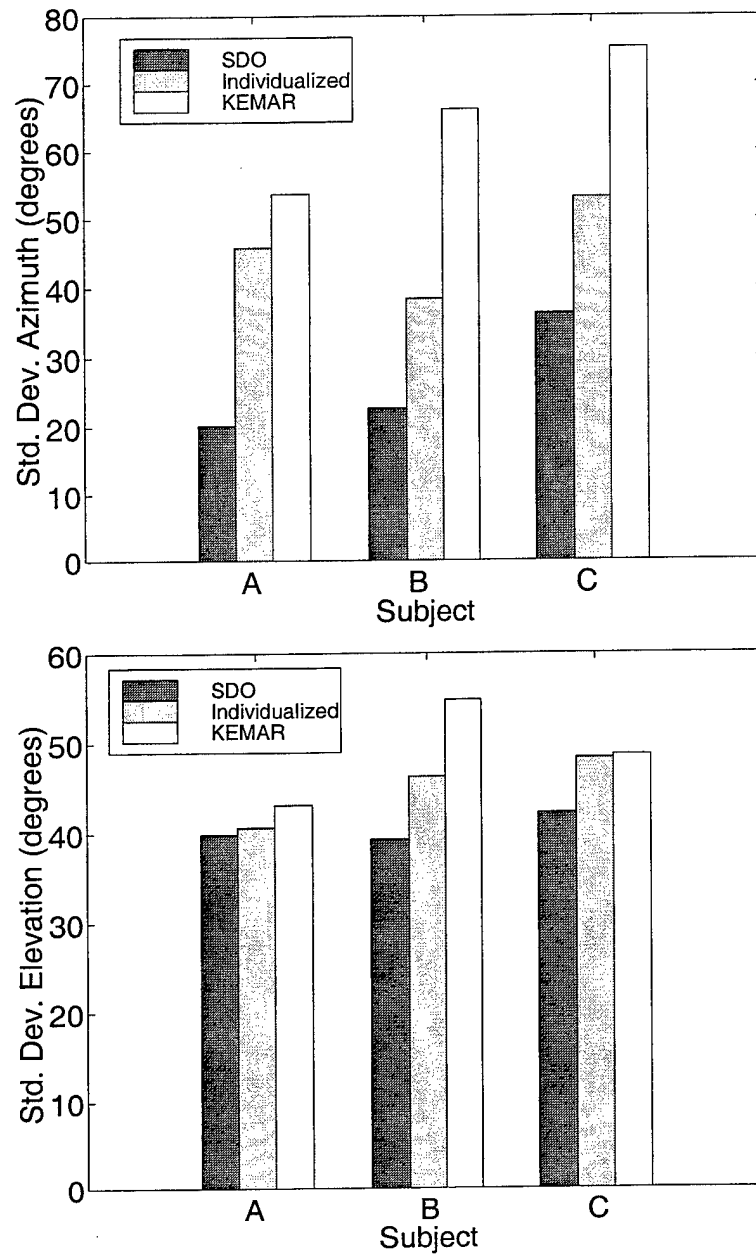


Figure 7: Standard deviation of error in azimuth (top) and elevation (bottom). Front-back reversals have been corrected in the azimuth data.

### **3.3.2 Evaluation of the HRTF measurements with the SNAPSHOT**

The data show that the individualized HRTFs measured with the SNAPSHOT system failed to provide any performance benefit over the generic SDO transfer functions that are supplied with the SNAPSHOT system. In fact, the individualized transfer functions measured with the SNAPSHOT system produced significantly larger angular errors than the SDO transfer functions ( $45^\circ$  vs.  $35^\circ$ ) and consistently produced a larger number of front-back reversals than SDO's transfer functions.

The individualized HRTFs measured with the SNAPSHOT did, however, produce significantly better performance than the KEMAR HRTFs measured with the SNAPSHOT. This is consistent with previous studies that have indicated that listeners can localize more accurately with HRTFs measured from their own ears than with generic HRTFs (Wenzel, 1991). However, it is striking that the majority of the degradation in directional accuracy with the KEMAR HRTFs is in azimuth (Figure 7), rather than elevation, while most previous studies have indicated that individualized HRTFs provide the greatest benefit to elevation performance (Wenzel, 1991). Furthermore, the number of front-back reversals was greater with the individualized HRTFs than with the KEMAR HRTFs, while most previous studies indicate that individual pinnae cues play an important role in disambiguating front-back confusions (Wenzel et al., 1993). It should be noted that the subjects exhibited a surprisingly large number of left-right reversals with the KEMAR manikin HRTFs, indicating that either the interaural time delay or the interaural intensity difference was not correctly represented by the KEMAR HRTFs measured with the snapshot system.

### **3.3.3 Explanations for poor performance with the SNAPSHOT**

The most likely explanation for the extremely poor performance with the individualized HRTFs (and the KEMAR HRTFs) is a failure of the SNAPSHOT system to adequately measure the HRTFs. The HRTFs were measured carefully according to the procedure outlined in the SNAPSHOT manual. However, there was some difficulty in adequately placing the microphones in the ear canals of the listeners. In fact, HRTF measurements were initially made with four subjects rather than three, but the fourth subject had to be thrown out because his HRTFs were greatly attenuated in the right ear due to improper placement of the microphone.

Another possible reason for poor localization accuracy with the SNAPSHOT HRTFs is that the SDO transfer functions include more points than the SNAPSHOT measurements

(144 vs. 72). This requires more aggressive interpolation of the transfer functions with the SNAPSHOT HRTFs, and may result in less accurate localization with the HRTFs measured with the SNAPSHOT system. Also, the SDO measurements were made with a spherical coordinate system rather than the cylindrical coordinate system required with the SNAPSHOT.

Note that the problems with the KEMAR manikin transfer functions may result from the difficulty in placing the SNAPSHOT microphones, which are designed to fit into a human ear canal, into the rubber pinnae of the manikin. These rubber pinnae have a very shallow ear canal and may not have properly accommodated the SNAPSHOT microphones.

## 4.0 CONCLUSIONS AND RECOMMENDATIONS

Based on this experiment, the SNAPSHOT system cannot be recommended for use as a tool to collect individualized head-related transfer functions. Although it does allow rapid collection of HRTFs (72 positions in less than 30 minutes) it has a number of serious drawbacks:

1. The HRTFs collected with the SNAPSHOT system produce consistently less accurate localization performance than the generic SDO HRTFs provided with the Convolvotron. This difference was significant for the individualized HRTFs collected on three different subjects. On average, the angular error was 25% larger with the individualized SNAPSHOT HRTFs than with the SDO HRTFs. There were also a greater number of front-back reversals with the individualized HRTFs. Thus, although the SNAPSHOT allows rapid collection of individualized HRTFs, these results suggest that the HRTFs collected with the SNAPSHOT are so poor in quality that any advantages of individualized vs. generic HRTFs are lost.
2. The processing performed by the SNAPSHOT when the measured HRTFs are stored as acoustic head maps (.AHM files) for use with the Convolvotron is not clear from the documentation provided. The manual suggests that this processing eliminates room reflections and the frequency response of the speaker from the measurements. However, no details are given. Furthermore, the ".AHM" file format is a proprietary format for the Convolvotron, and once the HRTFs are stored in this format it is impossible to examine them. The functions for the Alphasatron that are supposed to allow examination of the ".AHM" files (described in the manual) do not exist. Thus it is impossible to verify that the HRTF files have been properly collected without downloading them to a Convolvotron system.
3. The available documentation of the system is incomplete. Only a draft manual is available, which lacks figures and references. Furthermore, entire sections are missing from the manual and many of the functions documented in the manual are not available on the Alphasatron workstation.

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